Cryo-cooled Sapphire Oscillator With Ultra-High Stability

JPL

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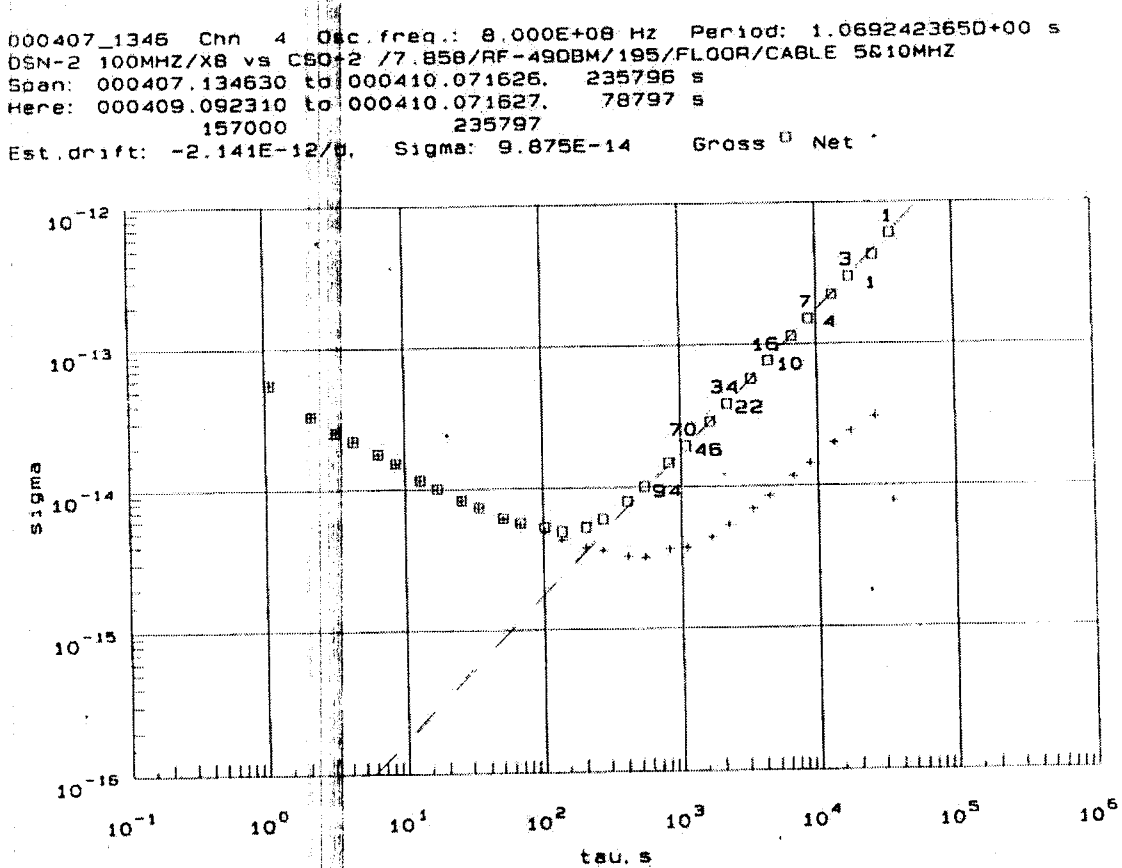
Compensated Sapphire Oscillator

Ultra-Stable Oscillator

- **The Compensated Sapphire Oscillator has demonstrated a stability of 3e-15 at 300S.**



Crucial Design Aspects

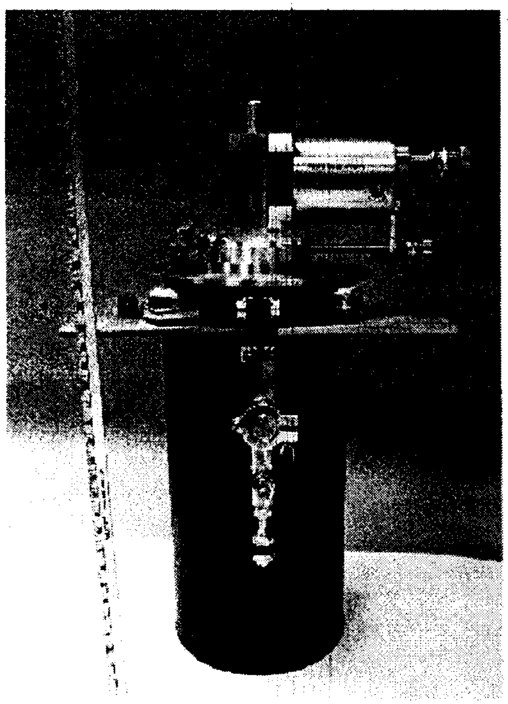
- **Cryocooler**
  - Cooling capability to give high Q sapphire resonator performance (T<10K) even with vibration isolation losses and with sufficient thermal margins to allow long term operation
- **Vibration Isolation**
  - Effectively isolate cryocooler and resonator without too much cooling loss
- **Resonator Design**
  - Adjustable compensation mechanism to raise and control widely variable turn-over temperatures in available sapphire (without degrading Q too much)
- **RF Electronics**
  - Allow 1×10^{-15} stability with Q's less than 1×10^{9}

These 3 aspects are strongly interrelated

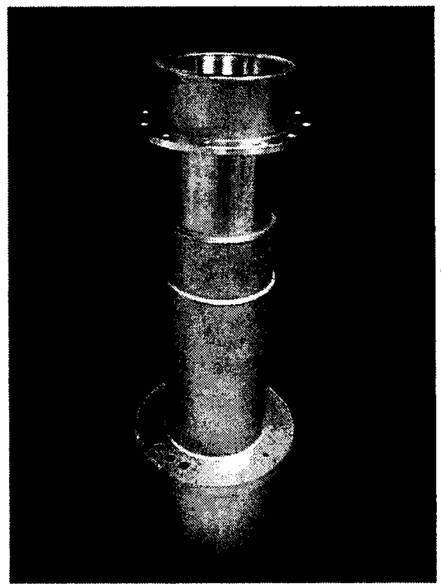
Compensated Sapphire Oscillator
CSO Technical Design/Status (Cont'd)

Cryocooled 10 K Sapphire Oscillator

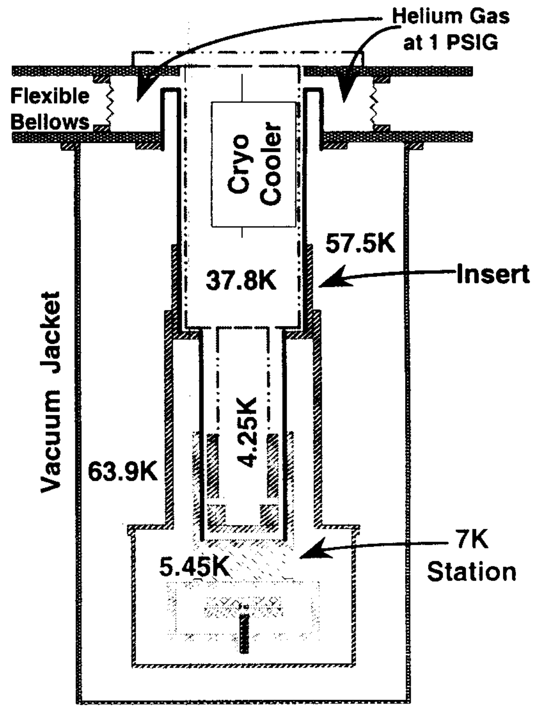
- First cryocooled frequency standard anywhere, first cryogenic standard appropriate for DSN



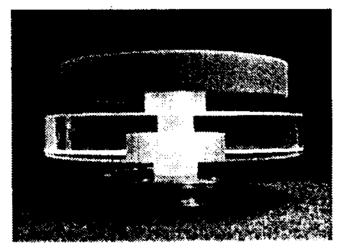
Cryostat and Cryocooler



Cryostat Insert

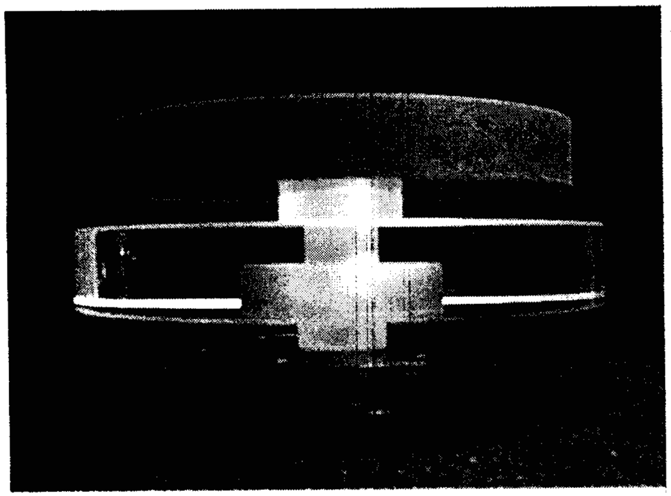


10K CSO Diagram

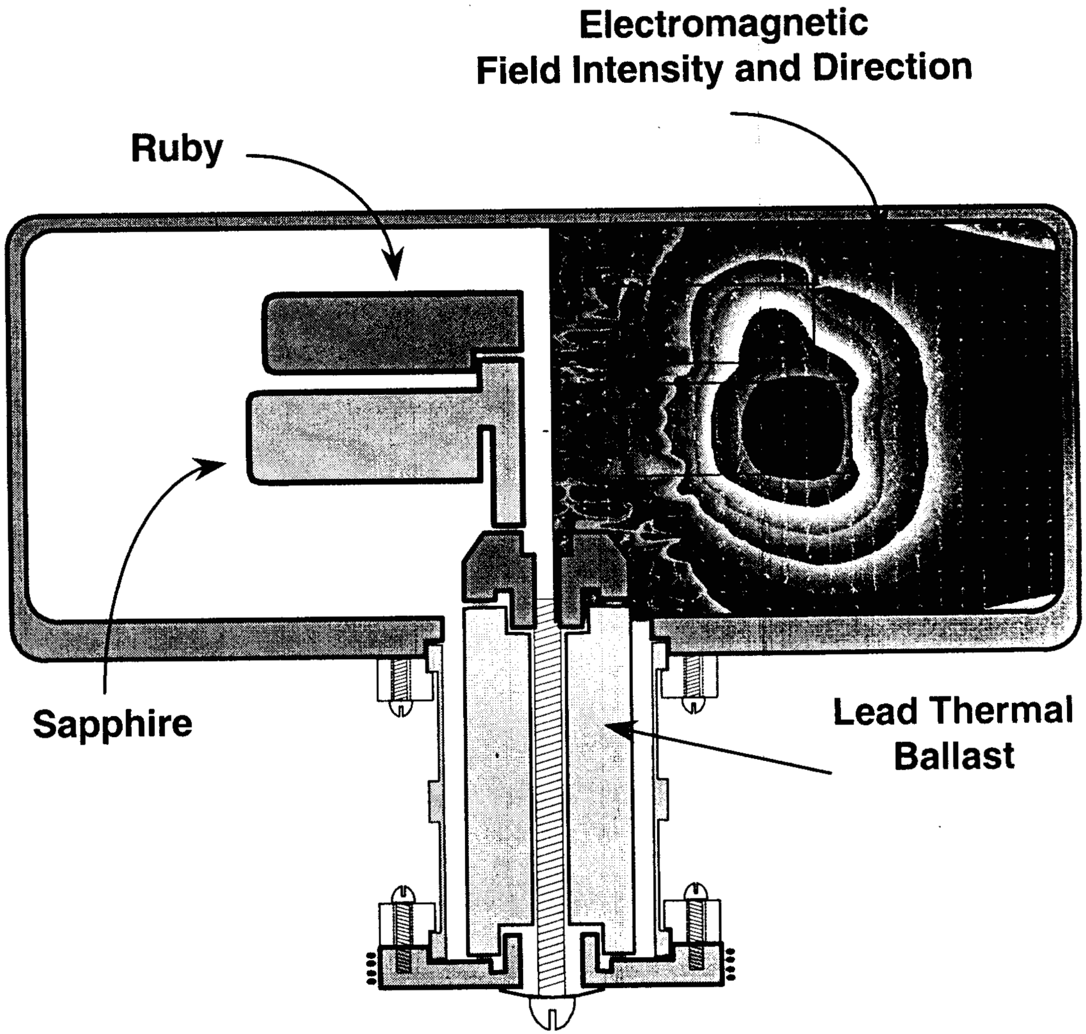


Ruby and Sapphire Resonator Elements

Resonator Design and Components



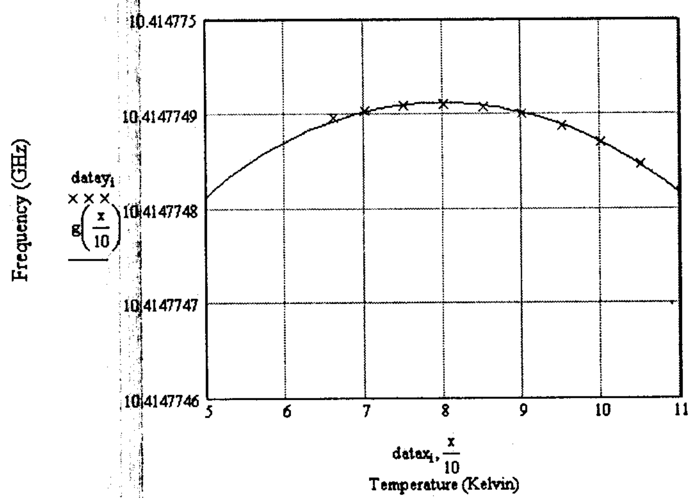
Ruby and Sapphire Resonator Elements



Compensated Sapphire Resonator Design

Turnover temperature of three CSOs
Tx=7.981 K for CSO #1,
Tx=7.845 K for CSO #2
Tx=7.336 K for CSO # 3

Example: CSO #2, Frequency =10.414 GHZ

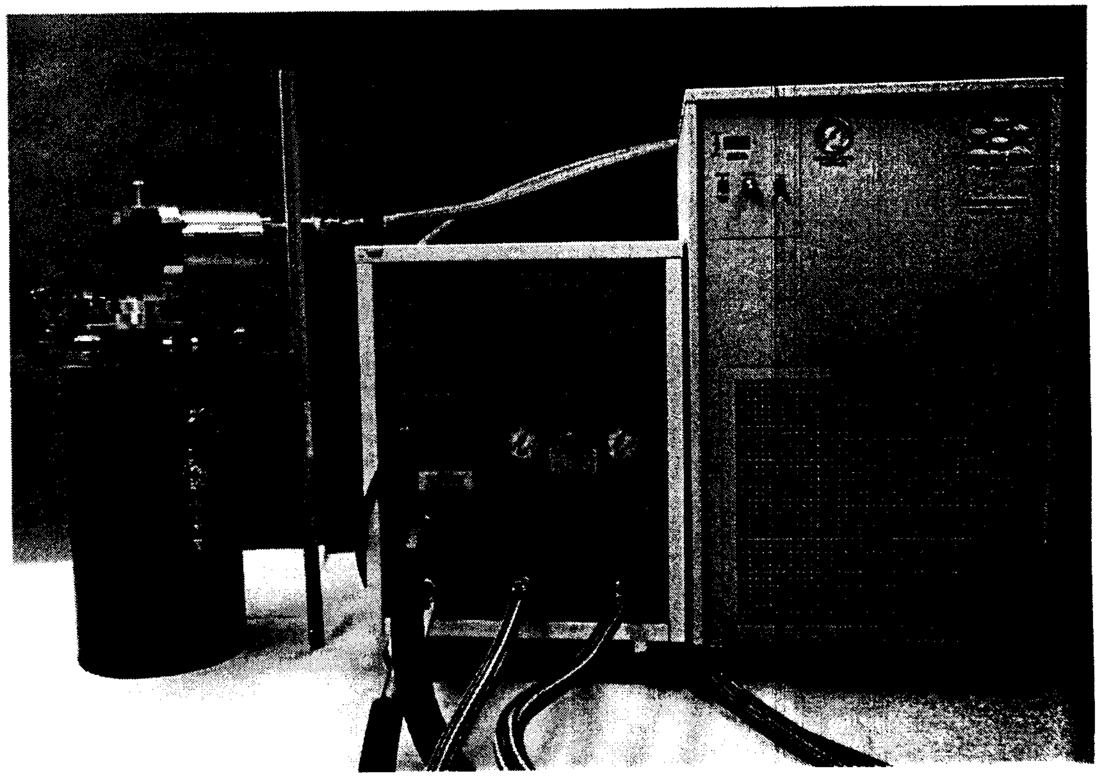


Compensated Sapphire Oscillator
CSO Technical Design Introduction

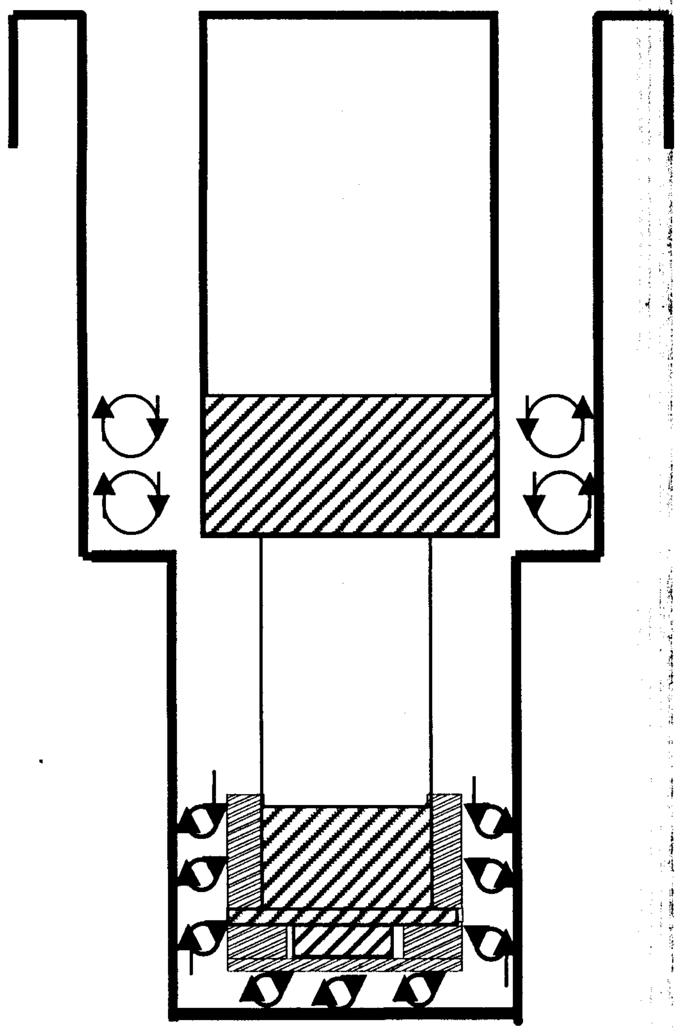
- Cassini Ka-band Expt. -- New science based on reduced frequency fluctuations
  - Solar wind (ionic) fluctuations reduced by frequency ratio 8GHz/32GHz
  - Available troposphere compensation improved with new JPL technology effort
  - Gravity Wave Search and RF Occultations need best possible frequency stability
- Cryo oscillator technology has performance but "not ready for prime time"
  - Has unparalleled close-in phase noise, short-term frequency stability
  - Liquid Helium replacement problems limit technology to research environment
    - Periodic replacement requirement not acceptable for most users
    - Helium gas incidents have large negative impact on frequency standards
  - Sapphire resonators are available that have reliable Q but they require helium cooling to reach their low (and uncontrolled) operating temperatures
- Cryo oscillator technology ready for boost
  - 2-stage 4.2K Giffard-McMahon (GM) cryo-cooler technology now commercially available
  - Vibration isolation requirements comparable to cryogenic Mossbauer work -- they solved by transferring heat with gravitationally stratified He gas at 1 atmosphere
  - 77K CSO, SCMO development at JPL provides technology basis
    - Externally compensated resonator designs allow adjustable operating temperature (turnover temperature) -- if it's not right, trim the compensating element and try again.
    - JPL-UTEP Finite Element capability allows great freedom of resonator design with excellent accuracy
    - JPL refinements to Pound ac frequency locking technique splits microwave resonance by larger factor than previously available -- frequency stability is 6 million times better than 1/Q

- Using new Leybold/Balzers cooler
  - First available 4K cooler using reliable 2-stage G-M technology
    - Obviates troublesome and expensive Joule-Thompson expansion stage
    - Incorporates scroll compressor, water cooling,
  - Somewhat more capacity than needed but available
  - Alternate unit is now on the market from Japan
    - Both units presently under test by S. Petty and group
- Temperature stability
  - Fast variation - smaller than expected apparently primarily due to helium gas acting as thermal ballast
  - Slow variations -- 3 stages of thermal control eliminate
- Reliability - seems pretty good but need to accumulate more data
  - First cold-head became hard to start after 4500 hrs
    - Factory repaired at no charge, "early model design"
    - Second unit now running
  - Compressor still ok after 5500 hrs

Cryocooler



CSO Helium Gas Heat Exchanger



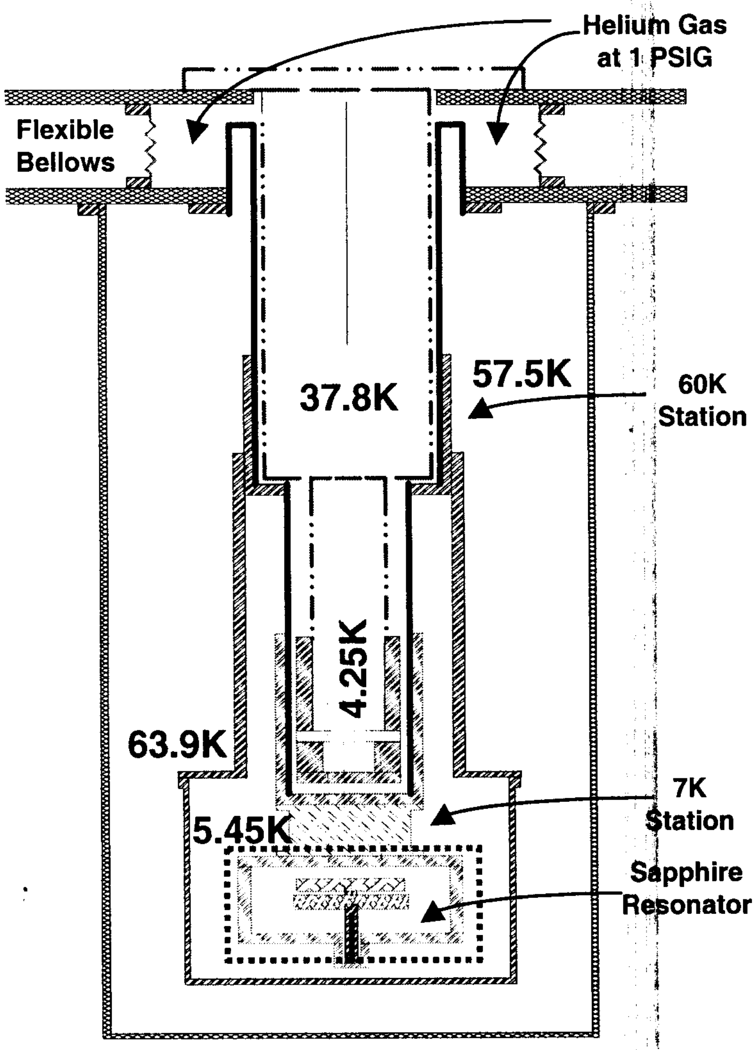
Helium Heat Transfer

Vertical plate			one inch extensio
gap(cm)	Ra	Nu	heat(watt)
0.2	1.87E+04	2.20	0.813
0.4	1.50E+05	3.88	0.620
0.6	5.05E+05	5.40	0.543
0.8	1.20E+06	6.84	0.498
1.1	3.02E+06	8.81	0.458
Horizontal plate			
gap(cm)	Ra	Nu	heat(watt)
0.2	1.87E+04	2.72	0.110
0.5	2.92E+05	5.09	0.082
1	2.34E+06	8.86	0.071
2.2	2.62E+07	18.97	0.068

Ra (Raleigh number) Nu (Nusselt number)

$Ra=\alpha g \Delta L^3/\kappa\nu$ $Nu=H/(\kappa\Delta/L)$

α=isobaric thermal expansion coefficient
g=acceleration of gravity
Δ=temperature drop between plates
L=cell height or gap space
κ=thermal diffusivity
ν=kinematic viscosity



10K CSO Measured Temperatures with 250mW into 7K Station

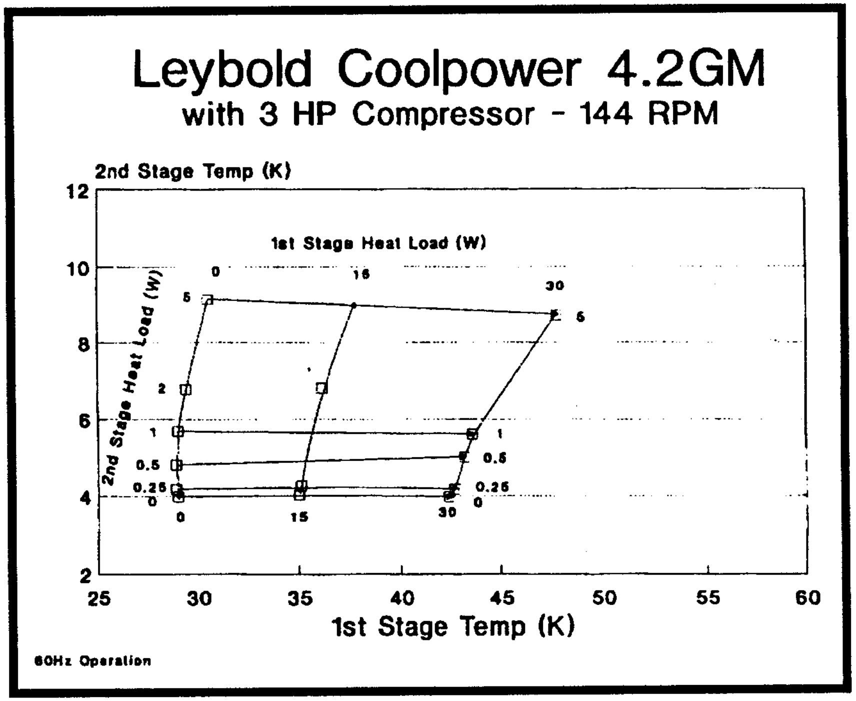
Thermal Design and Operation

Cooling Budget

Unit (Watts)

	Cold Head	Heat Load	Designed Heat Flux
First stage @ 38 K	38	5.18	8.11
Second Stage @ 4 K	0.25	0.113	0.72

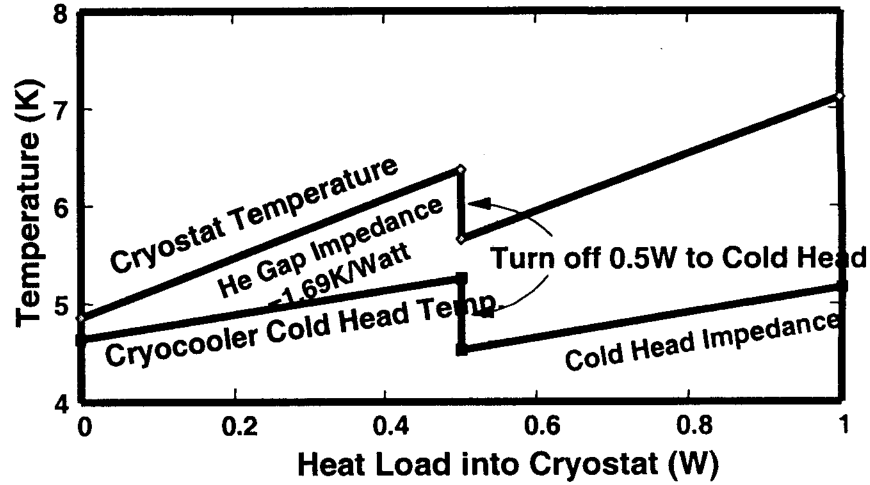
1/4 watt cooling at 4.2 Kelvin



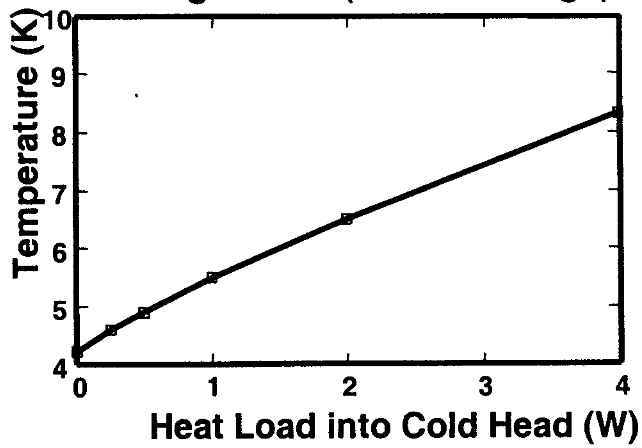
Cryogenic Testing

- Took delivery of cryogenic components
  - Closed-cycle refrigerator, compressor from Leybold/Balzers
  - Cryostat from Precision Cryogenics
- First test of cryogenic system
  - Three weeks continuous operation--no performance degradation with time
  - Verified temperatures and cooling power
    - Base temperature for 7K cryostat station is 5.45K with 250 mW added electric heat to simulate expected operational conditions
    - Measured temperature variation at 7K station is approximately 2mK p-p@2.5Hz cooler cycle frequency--much lower than expected 50mK p-p
    - Cooling power of cryocooler second stage verified--4.90K@0.5W heater input rising to 8.34K@4W input.
- Cool-down in 36 hours, warm up 48 hours

Thermal Impedance of Cold Head and He Gap



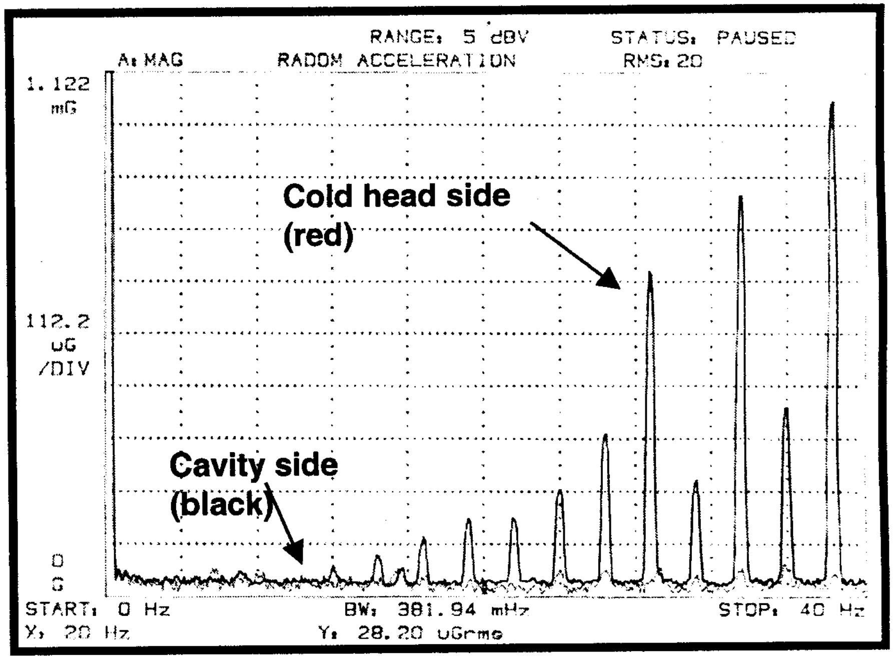
Cooling Power (Second Stage)

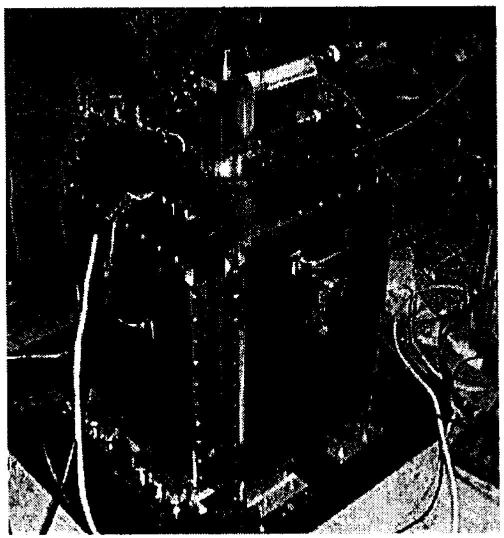


Compensated Sapphire Oscillator
CSO Technical Design/Status (Cont'd)

- **Vibration Isolation System**
  - Turbulent He gas heat exchanger at low temperature
  - Isolation bellows at room temperature
    - Metallic bellows proved too rigid
    - Neoprene bellows 0.055" thick
    - Size 10" OD to allow Dewar insert to fit through

Acceleration with and without Isolation





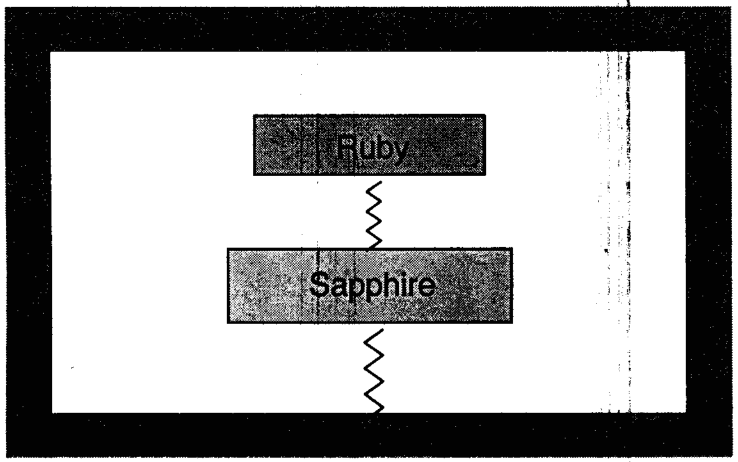
- Dewar and Cooler independently mounted to concrete floor
  - Low Frequency damper on Dewar side
  - Cork floor isolation for Cooler
  - Interpenetrating rigid boxes support Dewar and Cooler

Compensated Resonator Design

- **Basic Idea -- Externally compensated resonator as demonstrated in 77K CSO**
  - Add external element with opposite coefficient of frequency variation with temperature
    - Thermal design of resonator is crucial to performance -- if the two elements aren't at the same temperature it won't work
    - Need much weaker compensating mechanism at 10K than at 77K due to T^4 Debye dependence of frequency on temperature
    - Compensating mechanism must not destroy resonator Q
  - Develop design with thermally attached but weakly coupled ruby element
    - Sapphire resonators are already somewhat compensated (WGH modes) due to incidental paramagnetic impurities with 1/T frequency dependence
      - Naturally occurring paramagnetic impurities do not apparently ruin the Q so could possibly strengthen the compensation and raise the turn-over temperature from natural 4-6K to 8-10K
      - Early results on ruby indicate that Q's are probably still ok at fairly high Cr concentrations
    - Need to determine for sure ruby is ok
  - Design must not increase acceleration sensitivity -- would increase effects of cryocooler vibrations

Compensated Sapphire Oscillator
CSO Technical Design/Status (Cont'd)

Thermal Design for Externally Compensated Resonator



Shielding Can

Est. time constant between Sapphire and Ruby is

$\tau_{SR} \sim 0.1$ seconds

And between Sapphire and Can is

$\tau_{CS} \sim 1000$ seconds

Even though the can is weakly attached to the sapphire, a fast change in the can's temperature gives rise to a fast (0.1 sec) change in the temperature difference between sapphire and ruby given by: $\Delta T_{SR} = (\tau_{SR} / \tau_{CS}) \times \Delta T_{CAN}$

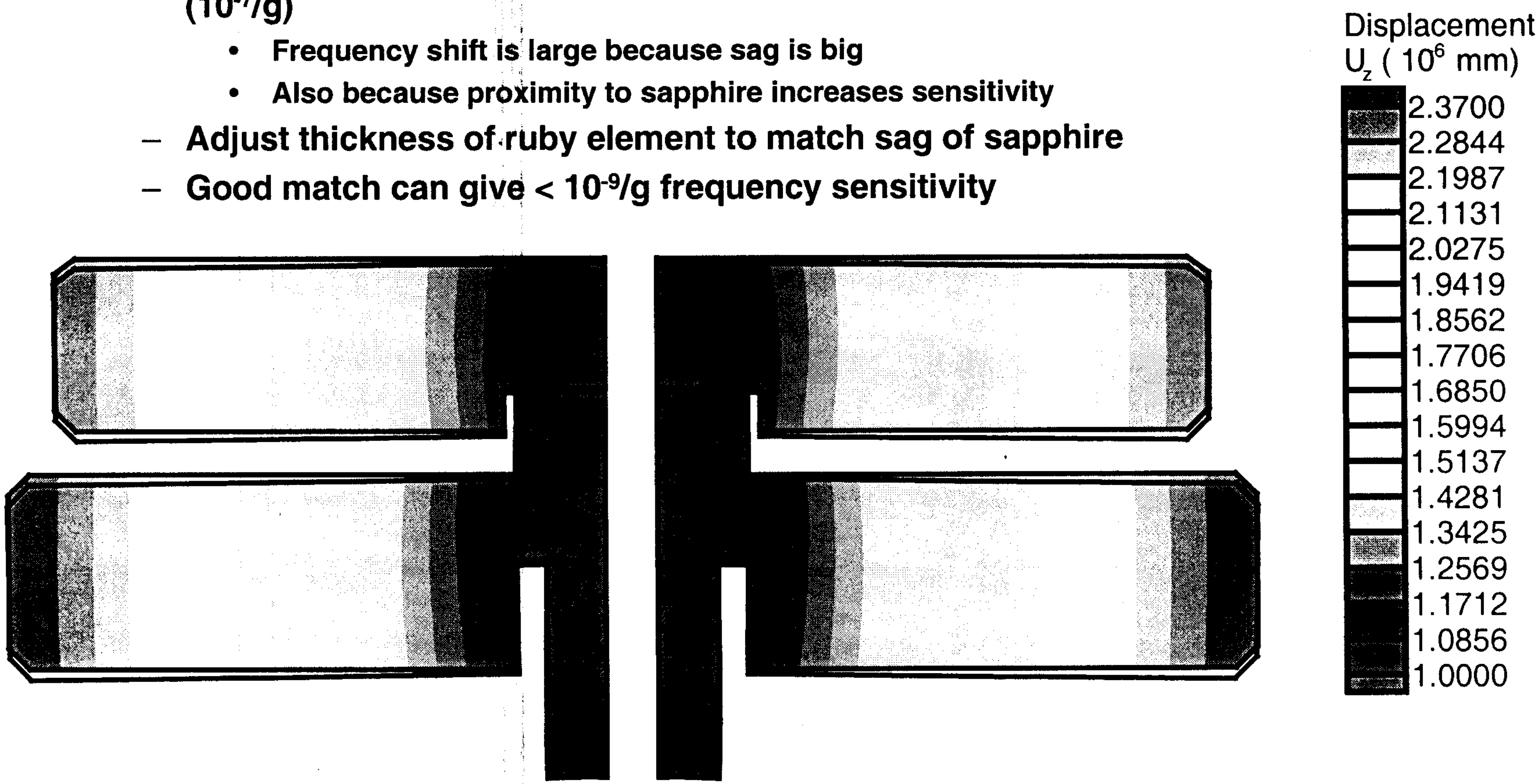
The sapphire resonator's temperature coefficient of frequency at 10K is approximately 2×10^{-9}, and so a 1 mdeg change in can temperature changes the frequency by:

$$\Delta\omega/\omega = \Delta T_{SR} \times 2 \times10^{-9}$$
$$= (0.1/1000) \times .001 \times 2\times10^{-9}$$
$$= 2\times10^{-16}$$

Compensated Sapphire Oscillator

CSO Technical Design/Status (Cont'd)

- **Gravitational sag in sapphire and ruby elements matched by Mechanical F. E. calculation**
- **Plug in sag as displacement into Electromagnetic F.E. calculation to estimate gravitational sensitivity of composite structure**
  - **Thin (1mm) ruby disk would allow compensation but give large g sensitivity (10^{-7}/g)**
    - **Frequency shift is large because sag is big**
    - **Also because proximity to sapphire increases sensitivity**
  - **Adjust thickness of ruby element to match sag of sapphire**
  - **Good match can give < 10^{-9}/g frequency sensitivity**



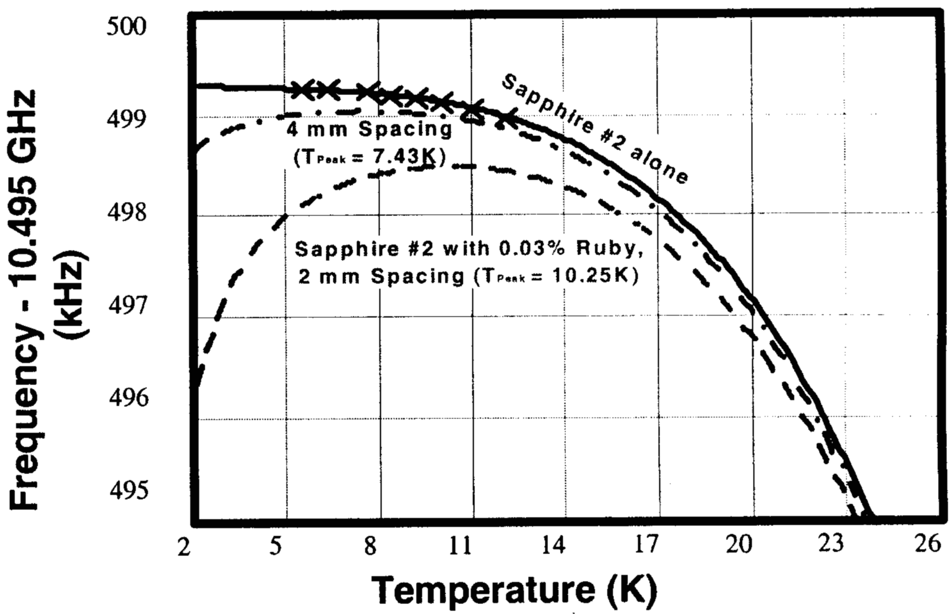
Compensated Resonator Design -- Turn-over Temperature

- Stable frequency requires operation at resonator turn-over temperature
  - At 8K, uncompensated frequency slope is 3×10^{-9}/K, would require 300 nano-kelvin regulation to achieve 10^{-15} stability
- Competing paramagnetic spin (1/T) and Debye expansion (T^4) frequency variations can provide compensation in sapphire and ruby
  - Sapphire with incidental chromium spins can show compensation below zero field splitting which is 11.44 GHz
  - Newly available sapphire without chromium (careful separation of sapphire and ruby processes by manufacturer) shows frequency independent compensation in microwave range since splittings of Ta, Mo, impurities are 100 - 1000 GHz.
  - Microwave coupling to spins depends on mode
    - WGH modes couple strongly to spins, WGE modes don't
- Previous practice of using incidental levels of paramagnetic impurity concentrations is inappropriate for anything but one-off demonstrations.
  - Turnover temperatures typically 4K - 6K for WGH modes for both old and new sapphire processes
    - Temperatures show too much variation for cryocooler operation
    - Temperatures are too low for vibration-free and reliable cryocooler cooled Dewar design
    - Of two new sapphire process resonators previously tested, both showed good Q, but one had turnover of 14K which is unusable
  - Achieving 2 crucial and technically challenging parameters (T_T and Q) in every sapphire is scary
  - At mercy of manufacturer's processes and markets

Compensated Sapphire Oscillator

CSO Technical Design/Status (Cont'd)

Sapphire, Expected CSO Temperature Dependence



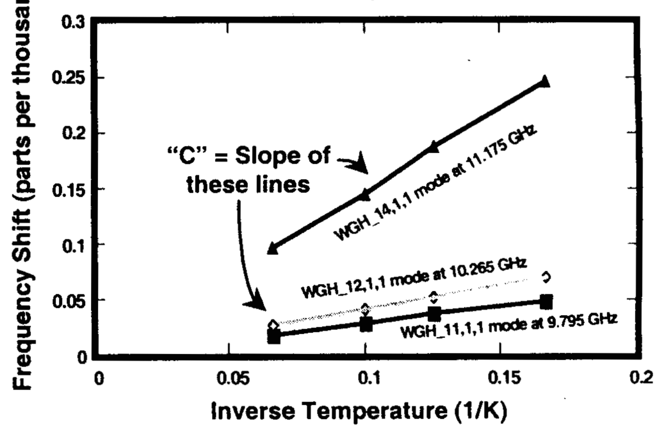
- Completed detailed compensation design
  - Measured ruby turnover temperatures are 20K - 40K, depending on mode, sapphire may or may not turn over
  - Thermal characteristics for both ruby and sapphire to be well modeled by 1/T and T^4 terms corresponding to Paramagnetic and Debye terms
  - Predict "as is" ruby turnovers of 7.43 K or 10.25K for 2mm and 4mm spacings, allows optimized operation without modifying the ruby elements
- Developed procedure for resonator evaluation
  - Adjust finite element model to show exact WGE mode frequency for Sapphire to match isolated sapphire resonator
  - Adjust 2 parameters of FE model for exact agreement with both WGE and WGH modes of isolated ruby resonator
  - Make FE calculation of magnetic EM energy in ruby sample when sapphire mode excited
  - Estimate energy in ruby WGM mode from B field angles in field views
  - Combine ruby 1/T component at 10.4 GHz with measured T^4 component for sapphire sample to predict turn-over temperature

Compensated Sapphire Oscillator

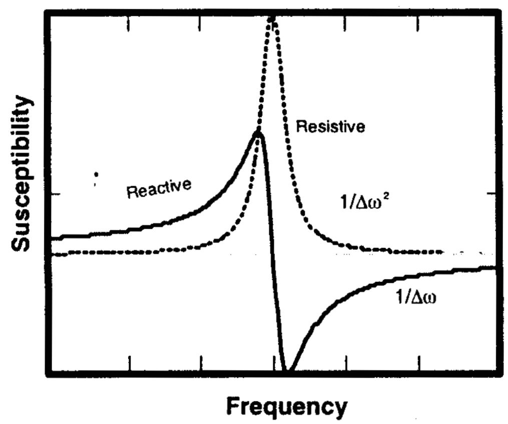
CSO Technical Design/Status (Cont'd)

- **Verified low spin-dependent losses in ruby while allowing compensation of sapphire resonator at 10K**
  - First simultaneous measurement of temperature tuning and Q in ruby
  - Confirm 1/T spin-dependent temperature tuning
  - Confirm Lorenzian frequency dependencies of both tuning and losses
  - Infer spin-dependent compensated resonator Q of 2 to 3×10^9 with 0.03% Cr doping, RF design requires Q of only 2×10^8
  - Confirm that only WGH modes couple to spins
  - Required ruby energy is < 1×10^{-3}, allows substantially non-resonant coupling, insensitivity to configuration

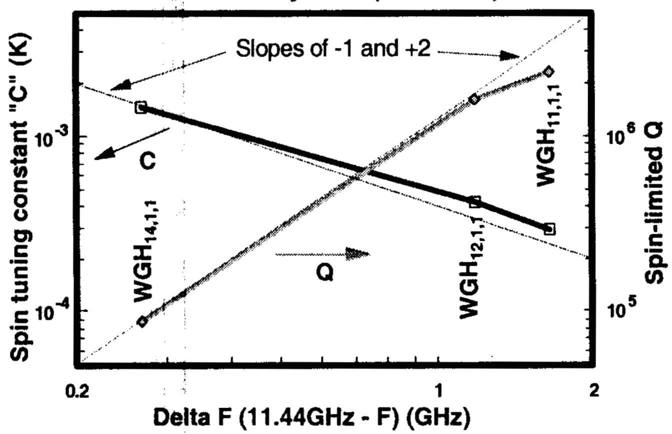
Spin-dependent frequency shift of 0.03% Ruby Resonator



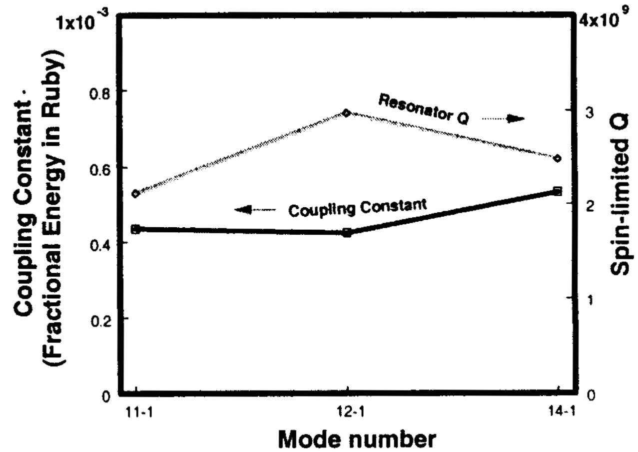
Expected Lorenzian line-shapes



Measured spin-dependent tuning and loss in Ruby disk (0.03% Cr)



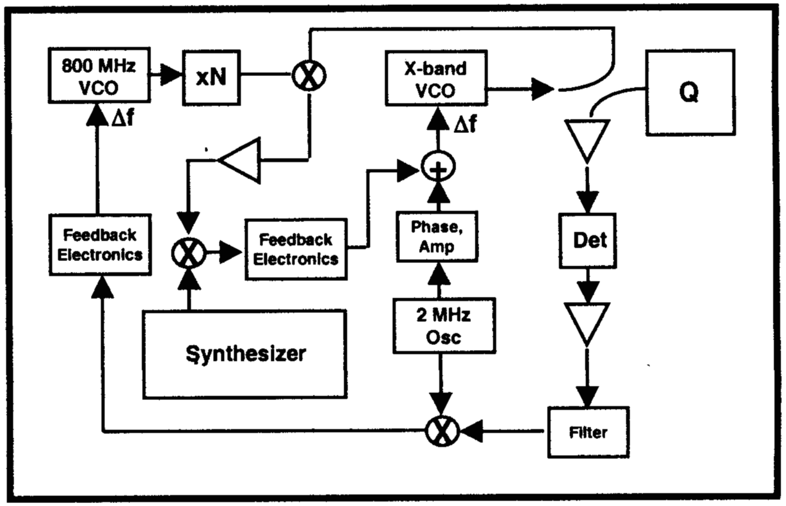
Inferred coupling constant requirement and spin-limited resonator Q



RF Electronics

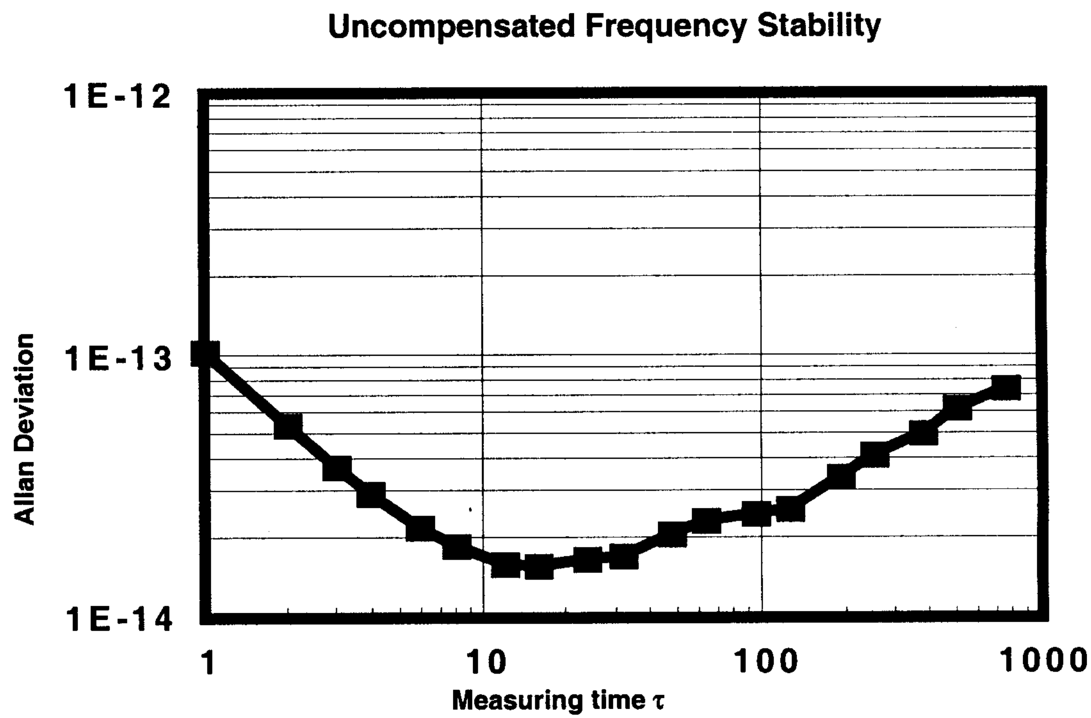
- **Design complete for 1-2x$10^{-15}/\tau$ RF interrogation system**
  - **Component phase noise impacts short term performance, overall requirement is 4x10^{-15} at 1 second**
  - **This level of performance not verifiable at 100MHz output frequency**
    - **Design for 1GHz output frequency**
    - **100MHz output may have higher noise**

10K CSO



Uncompensated Operation

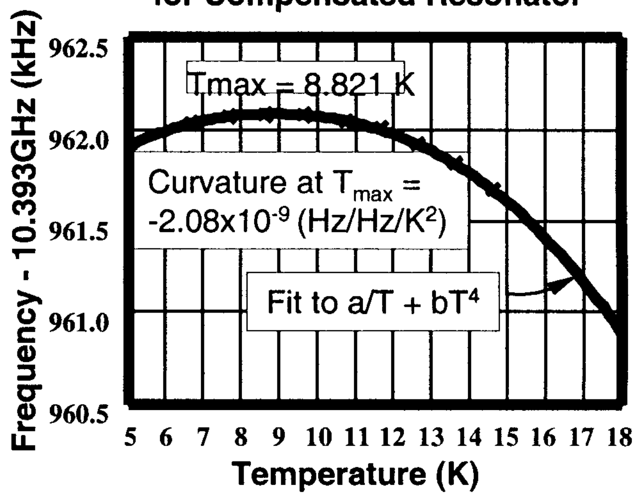
- **Stability measurements for sapphire #2 without compensation show < 2×10^{-14} stability**
  - First Ultra-High stability in a cryocooled oscillator
  - Large frequency slope of about 1×10^{-9}/K limits performance for bare sapphire (temperature variation ΔT of 10^{-5}K limits frequency stability to 10^{-14})
  - Operation within 0.010K of turnover reduces frequency slope to 1×10^{-11}, should enable thermally limited stability of < 1×10^{-15} for τ < 1000 seconds



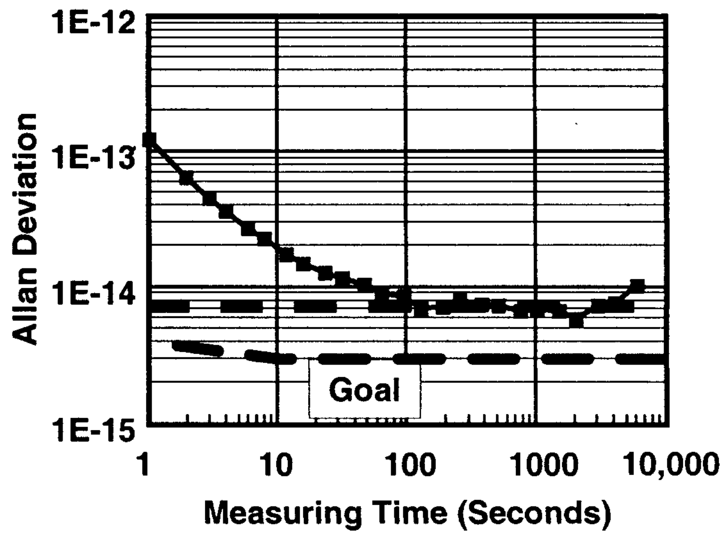
Compensated Operation

- Measured turnover temperature in first ever compensated sapphire resonator with adjustable turnover below 40K
  - Measured turnover at 8.821K compared to predicted 7.43K
  - Second assembly gave 8.54K
- Compensation response time is ~ 0.75 sec
  - Longer than 0.1 sec expected but allows reduction factor of 10 at 10 second measuring time and 100 at 100 seconds
  - Large thermal mass takes out short-term temperature fluctuations, can easily meet goals
- Measured stability of $7x10^{-15}$
  - First resonator assembly -- find afterwards sapphire has lowest Q of all of our samples
  - Short term stability follows H-maser ref
  - Floor not apparently due to thermal variation
    - 10^{-11}/dB rf power dependence is likely limit now, may need cryogenic rf level detection
    - Higher resonator Q may also improve floor

Temperature Dependence of Frequency for Compensated Resonator



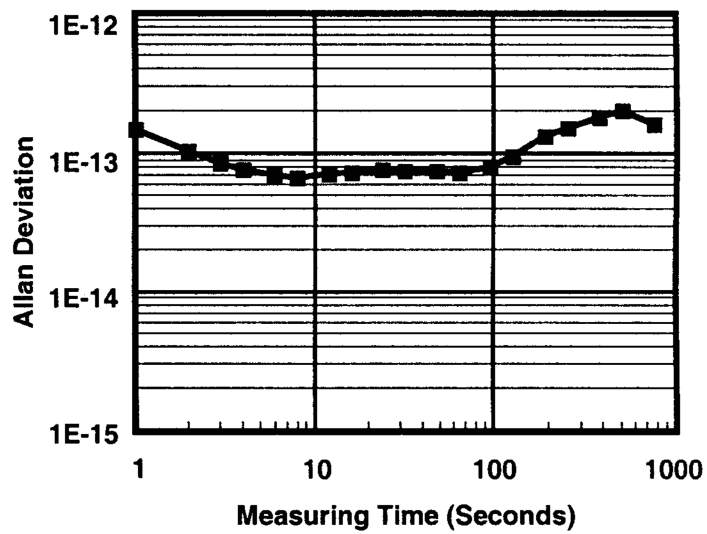
10K CSO Measured Stability Vs H-Maser

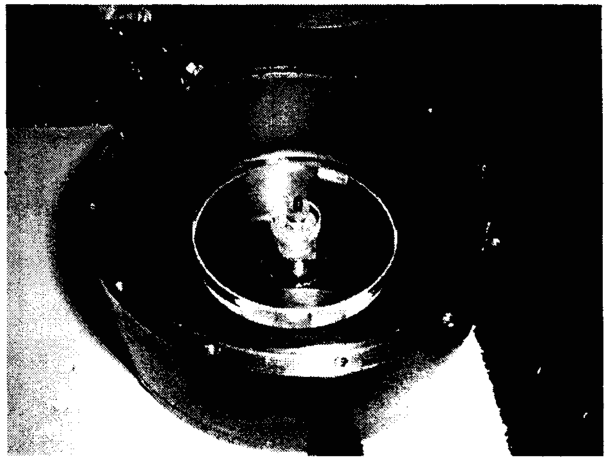


Compensated Sapphire Oscillator
CSO Technical Design/Status (Cont'd)

- **Development is on track, expect to have two working units this FY.**
  - Received sapphire, ruby elements for 6 CSO units
  - 3 cold heads, 2 dewars, 2 compressors in hand
  - Accumulated 6000 hrs on cryocoolers
    - First cold head cooling capability ok but hard starting required service
    - Second cold head now in use
- **Testing of resonator elements complete**
  - 6 Sapphire elements tested
    - Q's of six elements are 4@ 1 billion, 2@ 2billion.
    - First sapphire with lower Q sent back for post-machining anneal, retest shows Q improved x2
  - 6 of 6 Ruby elements tested
    - Tuning coefficients very close, should give turnover temperatures within 2%
    - Q's all good, limited by spin susceptibility
      - Tested ruby oscillator at 20K for mid-performance, cheap standard -- $1\text{-}2\times10^{-14}$ stability seems achievable

20K Ruby Oscillator Stability Vs H-Maser





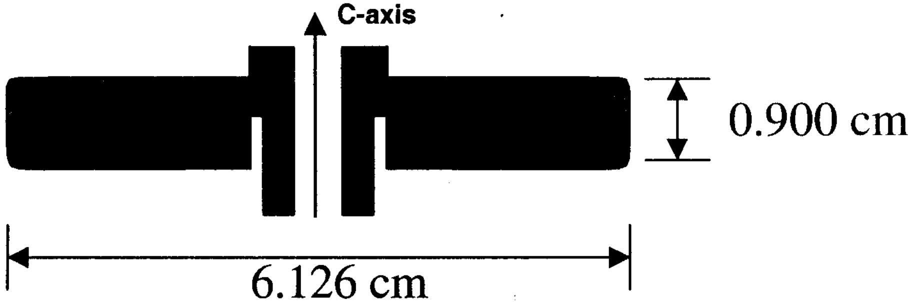
Sapphire element ready for test

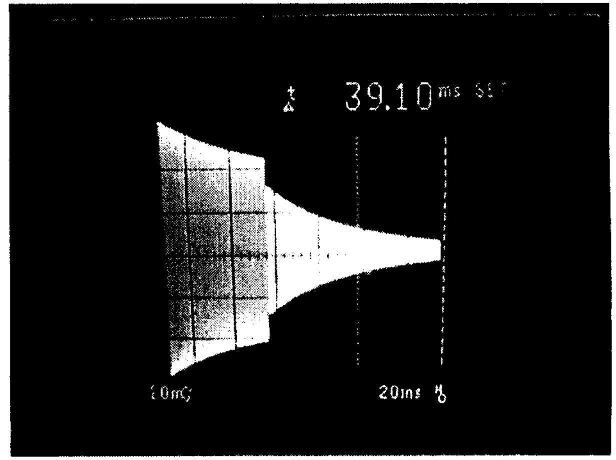
CSO Sapphire Cavities

Sapphire : Six pieces tested.

(a) Q measurement: $Q=1.28\times10^9$, F=10.404 GHz

(b) Geometry: To select TE n=14 freq. at 10.4 GHz from Finite Element Calculation and minimize g sensitivity.





(c) Frequency and Q variation:

Temp=10K		Sapphire Frequency (GHz)						
Mode ID	#1	#2	#3	#4	#5	#6	AVG	SD
14-2	10.395	10.396	10.416	10.395	10.400	10.404	10.401	0.008
1/f*df/dt(10^-9)	-6.61	-5.8	-6.7	-7.07	-3.41	-6.71	-6.58	0.42
T^4 (10^-11)	-1.99	-1.55	-1.77	-1.81	-1	-1.8	-1.78	0.14
Q	1.14E+09	9.80E+08	2.62E+09	9.80E+08	1.14E+09	1.96E+09		

Conclusion

- Three CSO operational with:
  - Stability: 7E-15 at 1S and 3E-15at 300S.
  - Demonstrated repeatability of CSO turnover temperature
  - Ready for first delivery to Deep Space Network.
  - Experience one year run time of coldhead.
  - Phase noise is 20 db better than H-maser. Still need to improve isolation design to decrease acceleration sensitivity.